LANSCE DIVISION RESEARCH REVIEW

Nuclear Cross Sections for Planetology

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Introduction

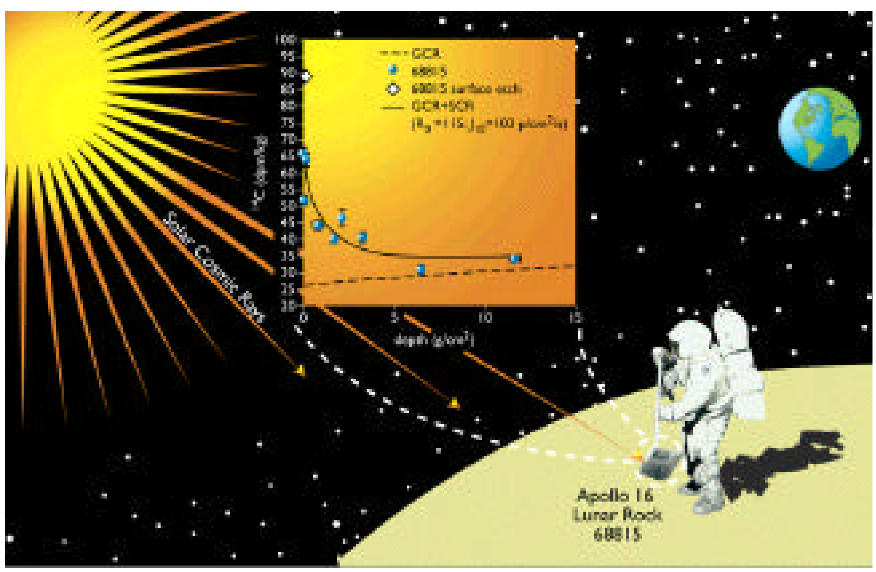
Cosmic rays interact with planetary materials to produce small quantities of radionuclides and stable isotopes. With the variety of measurement techniques now available, researchers routinely measure many nuclides in small samples taken from meteorites, lunar rocks and cores, and terrestrial rocks. From these measurements, the history of the object itself and the cosmic-ray environment to which it was exposed can be inferred. Good cross-section measurements for the production of these cosmogenic nuclides by cosmic-ray particles in common planetary materials are essential for these analyses, but many relevant cross sections have never been measured. We are conducting experiments at LANSCE to obtain average cross-section measurements using "white" neutron beams.

Examining Spallation Reactions in Planetary Material

Solar-cosmic-ray (SCR) and galactic-cosmic-ray (GCR) particles initiate spallation reactions in extraterrestrial materials. During high-solar activity, the sun emits SCR particles (~ 98% protons) infrequently, but when this activity occurs, the solar proton flux can be very high. These high proton fluxes can be a hazard to both humans and equipment in space. Most solar protons have energies < 200 MeV; these protons penetrate only the top 1 to 2 cm of a lunar rock (the density of lunar rock 68815 is 2.8 g/cm^3, for example); and only a small fraction of them initiate nuclear interactions. GCR particles (~ 87% protons, ~ 12% alphas, and ~ 1% higher-Z) can have energies as high as 10^{20} eV and can penetrate several meters into an extraterrestrial object, but the GCR flux is low. Most GCR particles initiate spallation reactions, generating many additional neutrons that also initiate nuclear interactions.

Primary cosmic rays interact directly with extraterrestrial bodies that have no atmosphere. These interactions produce cosmogenic nuclide records that contain information about the history of the object and the cosmic rays that fell upon it. Two archives available for analysis are the materials that were returned to Earth from the lunar missions and the meteorites collected on Earth.[1-5]

From the cosmogenic nuclide record archived in the lunar surface, we can learn about the sun's activity in the past. The analyses of activity-with-depth profiles measured in lunar rocks for several radionuclides and stable isotopes give estimates of the average solar proton flux over the past million years.[6] For example, from the analysis of the activity-with-depth profile for ^{14}C produced in lunar rock 68815 shown in Fig. 1 (from reference No. 3), an estimate of the solar proton flux over a time period



▲ ***Fig. 1.*** *^{14}C (dpm/kg) as a function of depth in Apollo 16 rock 68815,292. The plot shows the experimental measurements compared to a best fit for the solar proton flux plus galactic cosmic rays (GCR) (solid line), as well as the calculated GCR production, plotted as the dashed line. The higher surface value, which shows the effects of surface implantation by solar wind ^{14}C in the top few nanometers, is also plotted.*

characterized by the half-life of ^{14}C ($T_{1/2}$ = 5730 years) can be made. These estimates can then be compared to the direct measurements of the solar proton flux made over the last few solar cycles to see if the recent measurements are representative of the sun's activity in the past. As a result, better estimates of the shielding required and the hazards that might be met by both humans and equipment in future space missions can be made. That these hazards are real was shown in November 2000 when a powerful solar flare hit the spacecraft STARDUST, producing star-like images on the CCD cameras so that temporarily the spacecraft could not recognize its position in space.

The history of a meteorite or other extraterrestrial sample can be inferred from the cosmogenic nuclide record it contains. For example, activity-with-depth profiles were measured for several cosmogenic nuclides in an Antarctic meteorite identified as a lunar meteorite. From these analyses, estimates of how long the meteorite had been on Earth, how long it had been exposed to 4π cosmic-ray irradiation in space, and how long it had spent under 2π irradiation conditions on the lunar surface were made.[7]

The radionuclides that are of ten used to study variations in the solar proton flux over the past million years are given in Table 1. Recent advances in detection techniques—principally Accelerator Mass Spectrometry (AMS)—now allow the routine measurement of many of these radionuclides in small samples. The major constituents of lunar rocks include oxygen, silicon, aluminum, calcium, iron, and magnesium. (Nickel is an important element in iron.) The production rate for a particular isotope at any point in an object can be calculated by summing the contributions to the production at that point from all cosmic-ray particle interactions with all elemental constituents of the sample. This calculation can be made if, and only if, all the relevant cross sections for these interactions are well known. The measurements at LANSCE provide some of the necessary cross-section data required to make production-rate calculations of isotopes.

Good cross-section measurements exist for most relevant reactions initiated by protons (i.e., primary cosmic rays). However, there are very few cross sections measured for the production of cosmogenic nuclides by neutrons, which are needed to calculate the contribution to the GCR contribution from secondary neutrons.[8, plus references therein] The average cross-section measurements that we are making at LANSCE using "white" neutron beams are designed to partially address this need. Adjunct cross-section measurements using quasi-monoenergetic neutron beams at the National Accelerator Centre in South Africa[9] are also in progress.

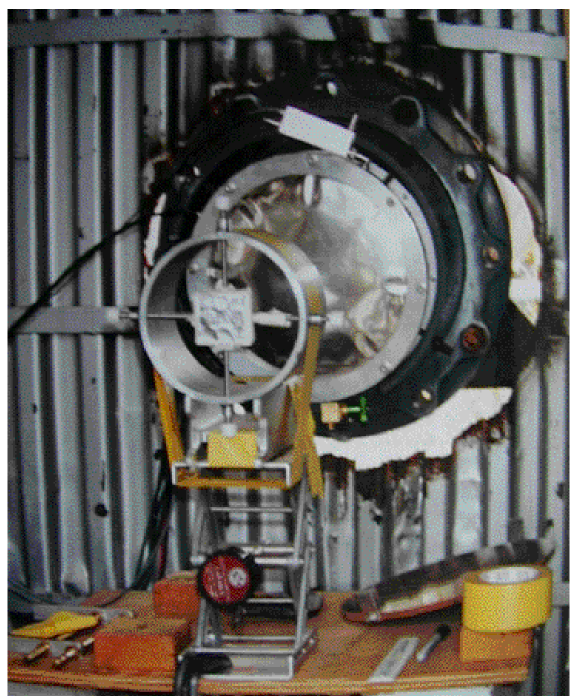
Table 1. Radionuclides used to study energetic solar protons*

Radionuclide	Half-life (y)	Major Targets in the Lunar Surface
^{37}Ar	0.096	Ca, K
^{56}Co	0.213	Fe
^{54}Mn	0.855	Fe
^{22}Na	2.6	Mg, Al, Si
^{55}Fe	2.7	Fe
^{3}H	12.3	O, Mg, Si, Fe
^{14}C	5730.0	O
^{41}Ca	1.0×10^5	Ti, Ca, K
^{81}Kr	2.1×10^5	Sr, Zr, Y
^{36}Cl	3.0×10^5	Ca, K
^{26}Al	7.1×10^5	Si, Al, Mg
^{10}Be	1.5×10^6	O
^{53}Mn	3.7×10^6	Fe

*Taken from reference No. 1.

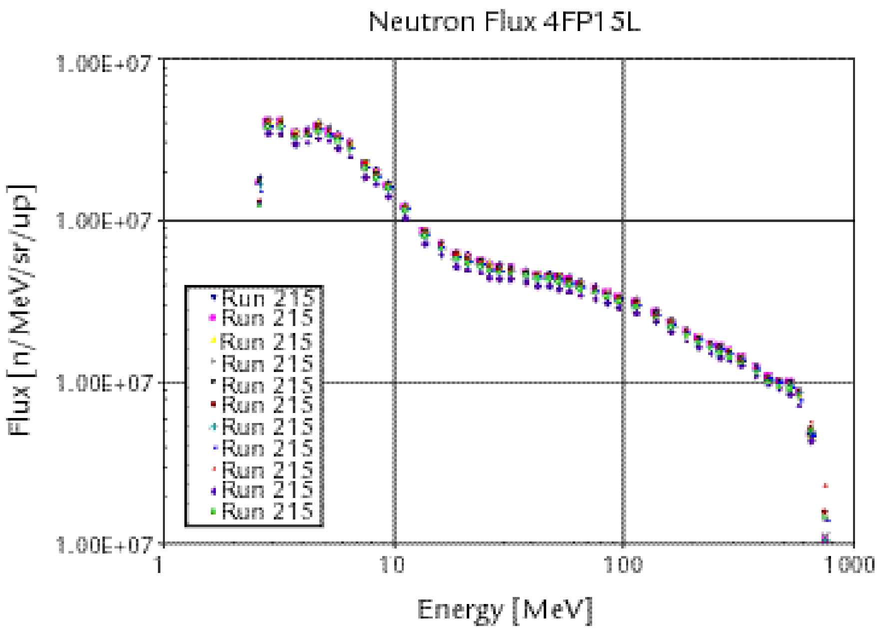
Experimental Setup at LANSCE

The experimental setup, shown in Fig. 2, is used to make the cross-section measurements in Flight Path



▲ ***Fig. 2.*** *Experimental setup in 4FP15L.*

4FP15L at LANSCE. Each irradiation is designed to measure the cross section for a specific target/product combination. The requirements of the AMS measurement constrain the irradiation time and the target weight and material. The target thickness is chosen to keep neutron losses at < 10%. The target holder is placed downstream of the uranium fission chamber used to monitor the neutron flux. Two inches of polyethylene placed well upstream attenuate the low end of the energy spectrum, so the energy range at the target holder is ~ 100 keV to 750 MeV. Typical spectra for the 2000 irradiations are shown in Fig. 3.



▲ ***Fig. 3.*** *Neutron fluxes from the irradiations in 2000.*

SiO_2 targets for the determination of the long-lived radionuclides ^{10}Be, ^{14}C, ^{22}Na, and ^{26}Al and Fe and Ni targets for the determination of ^{10}Be, ^{22}Na, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn by AMS with C, Al, Ti, Fe, Ni, and Au monitor foils have been irradiated in the 1998-2000 experiments. Short-lived radionuclides are measured in the targets and monitor foils using gamma-ray spectroscopy. Targets are sent for AMS analysis once these measurements are complete. Average cross-section measurements of the production of ^{7}Be, ^{22}Na, ^{24}Na, ^{46}Sc, ^{48}Sc, ^{48}V, ^{51}Cr, $^{52,54}Mn$, $^{56,57}Ni$, $^{56,57,58,60}Co$, and $^{194,196,198}Au$ in the appropriate target and monitor foils have been measured.

Conclusions

The experiments at LANSCE from 1998-2000 are providing new average cross sections for the production of radionuclides by neutrons that are needed for planetology. These measurements will give us insight into the magnitude of the contribution to the cosmogenic nuclide production in planetary materials due to secondary neutrons produced in primary GCR interactions. Many additional cross sections have been measured in both the targets and monitor foils that will be used in other applications, such as benchmarking Monte Carlo codes, terrestrial cosmic-ray studies, and input into shielding and radiation protection calculations.

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